A DECISION SUPPORT SYSTEM (DSS) FOR TRAFFIC INCIDENT MANAGEMENT IN ROADWAY TUNNEL INFRASTRUCTURE

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1. INTRODUCTION

The Italian roadway and motorway network is characterized by a high density of traffic and tunnels. In recent years the risks of incidents have increased as many road infrastructures, including tunnels, were designed several decades ago to carry lower traffic volumes than the current traffic levels and were built with technical requirements that with time have become outdated. Currently all the main Italian roadway and motorway companies are involved in the process to improve the tunnel safety levels according to the recent EU directive that defines minimum harmonised organisational, structural, technical and operational safety requirements for all tunnels longer than 500 meters in the Trans-European Road Network.

The SITI project, leaded by the TRAIN Consortium (an Italian association for industrial researches in the field of transport) and co-financed by the MIUR (Italian Research Ministry), is aimed to study, develop and demonstrate a set of innovative technologies to improve the traffic monitoring processes and the safety levels inside tunnels.

The project introduced a new approach to the matter: the “Dynamic Tunnel” vision considering tunnels as a whole with the road network before and after, like a complex system in continuous evolution.

Among the main objectives, the SITI project included the realization of a DSS to help traffic control centre (TCC) operators and supervisors for the selection and best implementation of traffic management measures in response to the occurrence of an incident, with the aim to minimize incident negative consequences on traffic, as formation of congestion and queues, travel delays and risks for secondary incidents.

Actually incidents in tunnels, though they are not so frequent, have more serious consequences than those in the open, in terms of human lives and infrastructure repair costs, but also for their negative effects on traffic congestion.

The present paper describes the current development of the TRIM (Traffic and incident management) system: a DSS designed to assist traffic control centre (TCC) teams to effectively and safely manage traffic flows and mitigate traffic congestion in the event of an incident, in particular an incident inside a tunnel or along the surrounding roadway.

The TRIM system has been conceived and designed by an ENEA (Italian National Agency for New Technologies, Energy and the Environment) working group for the TRAIN Consortium, within the SITI project. Including a traffic simulator at macro-scale and a micro-simulator as well, TRIM is able at preventing crisis situations and at making more effective the traffic control operations during emergency events, both at local and at a wider area as well.

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In particular TRIM is designed to support at the same time an off-line task of traffic supervisors, like the study and formulation of proper traffic diversion emergency plans, and some on-line tasks of TCC operators, like the early estimate of impact area and incident duration and the selection of the most suitable traffic response plan, based on a set of parameters such as the incident severity level, the estimated duration and the current/predicted traffic demand approaching the incident site and across the overall road network. The post-incident traffic management strategies supported by TRIM includes the activation of proper traffic control measures at the incident site and on the roadway infrastructures affected by the traffic incident and the dissemination of information to drivers.

For this purpose TRIM will be interfaced with all the existing local traffic control devices (traffic lights and VMS) and with travel information systems including WEB and mobile phone.

Although TRIM is born in the SITI project framework, the system in perspective will not be “tunnel dependent”; it can work as well inside a TCC of a motorway or of an urban area, where it can be linked with the existing equipment providing real time data collected from traffic sensors.

By reducing the duration of the incident and maximizing the use of the available roadway capacity during incidents, both the economic cost of congestion and the associated aggravation can be reduced. The result is more reliable travel, shorter trips and an ability to accommodate more trips within the existing roadway infrastructures.

2. BASIC ELEMENTS ABOUT INCIDENTS AND TRAFFIC MANAGEMENT

The occurrence of incidents, besides its direct impacts in terms of property damage, injuries and fatalities, can quickly lead to congestion and associated travel delay, wasted fuel, increased pollutant emissions and higher risk of secondary incidents.

Traffic management in the post-incident scenario is a primary tool in minimizing the impact and reducing the probability of secondary incidents and is a crucial step to minimize the negative consequences on network efficiency and safety.

The basic elements of an emergency response plan are the traffic channelling and control schemes to regulate traffic flow past the incident site, the traffic diversion on appropriate routes to relieve traffic demand at the incident site and the dynamic dissemination of information to drivers using various output devices and regarding traffic conditions, changes in roadway geometry, operating traffic speeds and routing.

2.1 Incident phases and duration

An incident represents any unpredictable occurrence that disrupts traffic flow for a period that lasts longer than the incident itself and, temporarily, reduces roadway capacity.

An incident can range from disabled vehicles or debris dropped along the side of the roadway up to major collisions involving fatalities, fires or hazardous material spills.
Severe incidents involving significantly damage to roadway and structures, such as multi-vehicle collisions, tanker truck explosion and fire in tunnels, can cause severe disruptions in the flow of traffic including even disturbances in the economy of a whole region. However minor incidents, such as disabled vehicles, are responsible for the majority of the total delay caused by incidents. The amount of delay and impacts that results from the incident depends on the duration of the following five distinct phases often overlapping:

1. **Detection** that determines the occurrence of the incident;
2. **Verification** that defines the precise location and nature of the incident;
3. **Response** that concerns the activation and dispatching of personnel and equipment to the incident site;
4. **Clearance** that includes the removal of vehicles, debris and spilled material from the roadway to restore the complete roadway capacity;
5. **Recovery** that consists of dissipating the queue at the site of the incident once the roadway is cleared in order to restore as quickly as possible the normal traffic conditions.

Together the first four phases represent the total duration of the incident or the period of time ranging from the occurrence of the incident to the complete restoring of the roadway capacity. The recovery phase largely depends on the extent of the disruption to traffic flow caused by the incident and on the effectiveness of the traffic management measures implemented soon after the occurrence of the incident.

### 2.2 Measures at the incident site

Traffic management includes the implementation of a range of traffic control measures at the incident site and on the roadway infrastructures affected by the incident aimed at minimizing traffic disruption, reducing the probability of secondary collisions and protecting responders working on the incident. The control at the incident site is required to facilitate the orderly and safe movement of traffic past the incident by channelling traffic with flares, cones, delineators and warning signs into the lanes that remain open to traffic. Typical techniques implemented for the on site control are:

a. roadway shoulder utilization to provide additional capacity around the incident scene;
b. ramp diversion from the exit ramp immediately preceding the incident site, to divert traffic temporarily off the roadway onto a nearby parallel street and back onto the affected roadway downstream of the incident scene;
c. contra-flow lane diversion (for major incidents causing the full closure of the carriageway for several hours) to allow upstream trapped traffic to utilize a travel lane from the opposing roadway direction;
d. alternate one-way movement when two-way traffic is reduced to one-way traffic and traffic in both directions must use a single lane. Alternate one-way traffic control may be effected by means of temporary traffic signal or by flagmen.
2.3 Limiting traffic demand

Traffic management may also require the implementation of measures that temporarily limit traffic demand approaching the incident location to prevent congestion or vehicle queuing upstream of the incident.

In this context, typical traffic control strategies are traffic diversion on alternative routes and ramp metering.

By effectively controlling entering vehicle volumes with traffic signals at the entrance ramps located upstream from the incident site, the ramp metering strategy can help keep the traffic density below the critical level and provide a smooth flow of traffic on the section of roadway immediately upstream of the incident.

The diversion of the traffic flow approaching the incident area on appropriate alternative routes is the only way to alleviate congestion especially in the occurrence of major incidents requiring the long-term closure of multiple lanes or full closure of the roadway.

However, the effectiveness of traffic routing depends on the availability of alternate routes and their level of congestion.

A diversion strategy involves the determination of where and how much traffic should be diverted and the sequence of roads forming the diversion routes that are best suited to handle this increased traffic demand.

A diversion strategy may also involve the modification of signal timing and the activation of guide signs along the diversion routes to allow the effective and safe passage of diverted traffic.

2.4 Information to drivers

A major element of traffic management in post-incident scenarios is the dissemination of information to drivers approaching the incident area regarding traffic conditions, changes in roadway geometry, operating traffic speeds, and routing by deploying various output devices (variable message signs, lane control signals, radio broadcasts, etc).

Drivers’ response to the provided incident-related information is crucial for successfully diverting traffic, reducing secondary incidents, and improving responders’ safety on the incident scene.

3. TRIM FUNCTIONS

In this context, a DSS with the capability of storing, analyzing, and displaying geographically referenced information and data on network characteristics, traffic and incidents, predicting incident duration and traffic delay, generating and implementing appropriate traffic response plans to different incident scenarios, and controlling their effectiveness in reducing traffic disruption and related impacts, appears to be the perfect tools to greatly increase the efficiency of incident and traffic management.

TRIM was conceived to carry out the following specific functions:

- to integrate and display information flowing from the surveillance and control devices, installed inside the tunnel and on the surrounding road
network, to the TCC (i.e.: traffic flow sensors, traffic signs, VMSs, meteo sensors, AVL, etc.);

- to perform traffic simulation studies at macro/micro scale to evaluate feasible traffic response plans under different traffic conditions and incident scenarios;
- to store, query and analyse network characteristic data, incident scenarios and historical traffic data, needed to define possible diversion routes and control strategies and to feed traffic simulation and prediction models;
- to select on the basis of predefined rules the most appropriate traffic plan in response to an incident and suggest to the TCC operators the needed steps for its implementation;
- to provide during the incident management period reliable estimates of the network traffic conditions to verify the effectiveness of the proposed traffic response plan.

Based on these requirements TRIM design is aimed to make available a new software tool suitable to help the TCC operators in their tasks, especially when they face dramatic traffic congestion caused by major incidents inside or in the proximity of a tunnel, involving long duration clearance operations and affecting high traffic volumes.

In particular TRIM is designed to help the TCC operators to effectively perform:

- off-line tasks, concerning the study and design of a set of traffic response plans to face possible incident scenarios through the use of micro/macro traffic simulation and prediction tools;
- on-line tasks during the incident management process, concerning the selection, implementation and follow-up of the most appropriate traffic response plan, in relation to the incident severity level and the traffic demand approaching the incident site.

The main off-line and on-line functions of the TRIM system are outlined in the flowchart illustrated in figure 1. The flowchart shows the different steps followed from the occurrence of the incident to the implementation and control of the traffic response plan.

3.1 On-line tasks

After an incident has been detected and verified through information coming from the different available sources (traffic sensors, CCTVs, police patrole, etc.), the incident characteristics (i.e.: type, location, time of occurrence, vehicle involved, injuries involved, fatalities involved, etc.) are fed by the TCC operators into TRIM through a convenient graphical user interface (GUI).

Once TRIM has received input information describing the incident, the first step is to estimate the incident duration on the basis of the operational experience accumulated from previous incident management operations. Duration forecast, which refers to the expected time interval ranging from the incident occurrence to the end of clearance operations, is made by TCC operators directly or using a suitable prediction model incorporated in TRIM.
Starting from the predicted incident duration and taking into consideration the reduction in roadway capacity and the current/predicted traffic demand, TRIM estimates the impact area extent and the travel delays that will be caused by the incident.

All these estimates are then used to select a preliminary traffic response plan specifying the set of strategies chosen to manage traffic flow (such as diversion points, % of diverted traffic demand, termination points, diversion routes, new timing for traffic signals, emergency signals, messages to be displayed on the VMSs, etc.). The plan selection is performed by TCC operators, with the help of a specific TRIM software module, on the basis of a set of rules pre-defined by the traffic experts. According to the selected traffic response plan, TRIM proposes to the TCC operators, step by step, the predefined traffic management measures to be implemented. The traffic response plan is integrated with information about the best paths to be taken by the involved emergency response vehicles to reach the incident site more quickly and vice versa.

Traffic micro-simulation is then performed, starting from the preliminary estimates about the incident duration, the current traffic data received from sensors, the selected alternative routes and the other traffic control measures taken by the TCC operators, according to the selected response plan. Traffic micro-simulation reproduces in a virtual environment the spatial and temporal evolution of the traffic flow on the roadway network affected by the incident with the final aim to offer an immediate, reliable estimate of the effectiveness of the preliminary traffic response plan.
If the micro-simulation results (such as delays and queue lengths) differ significantly from the expected traffic performance, TRIM helps the TCC operator to select and implement a new and more effective traffic response plan.

On-line traffic micro-simulation can be performed again when updated information on the actual traffic demand or about the actual duration of clearance operations become available in order to verify the effectiveness of the traffic response plan under implementation.

3.2 Off-line tasks

The TRIM off-line functions are aimed to study and evaluate feasible traffic plans in response to possible incident scenarios through the use of micro and macro scale traffic simulation models.

Micro-simulation, that captures the behaviour of vehicles and drivers in great detail, is performed to evaluate traffic congestion evolution at local scale, in the proximity to the incident site, due to the complicated structure of the models involved.

On the other hand macro-simulation, due to their more aggregate nature, is performed to evaluate the traffic conditions at a wider scale (i.e.: regional/national network), to choose the best diversion points for the specific incident and to determine the best alternative routes for the chosen diversion points.

Finally, an additional off-line function of TRIM is the generation of shortest paths, so that emergency responders can avoid blocked or slow routes and quickly reach the incident site.

4. GENERAL ARCHITECTURE AND SOFTWARE MODULES

4.1 General architecture

TRIM is designed to work inside a traffic control centre (TCC), able to perform traffic surveillance, traffic control and driver information functions, of a motorway, an urban area or a long tunnel.

The general architecture of the TRIM system is illustrated in figure 2. below.

The architecture of TRIM software is derived from the Mobility system, a DSS for urban traffic planning, and from Merlino, a DSS for on-line traffic management, designed and implemented by ENEA during the past years.

TRIM architecture includes a traffic simulator at macro-scale (MIAURB from D’APPOLONIA), which is directly embedded in the system software architecture, and a micro-simulator (AIMSUN) that will be linked with the system as well.

Traffic simulators will enable TCC operators to perform detailed real-time analysis of the network traffic conditions under the current control strategies during the incident management period.

Figure 3. here below shows the connections between the main software elements of the system: the Data Base (DB), the GIS (Geographic Information System), the Graphic User Interface (GUI), used by operators and
supervisors, and the traffic simulators at macro-scale and micro-scale (SIM) linked with the system.
The software architecture and the modules composing the TRIM system are shown in figure 4. Here below.

Figure 4: TRIM software modules
4.2 Software modules

TRIM is composed of

- a relational database (MySQL) designed to store, query and update historical incident data, traffic data, traffic network characteristics, data exchanged between the various system modules, simulation results and traffic response plans.

The main information families (macro-entities) stored in the alphanumeric Data Base are indicated in Fig. 5 here above.

- a GIS-based user interface (ArcView) that enables TCC operator to display the roadway network, the real time traffic data and the status of the control devices on a background map, to run on-line and off-line prediction and simulation procedures, to analyse and display the results in multiple views and tables, to define and implement traffic response measures;

and of the following software modules (shown in the previous figure 4.):
- an interface module to gather *on-line traffic and meteo data* collected by sensors installed inside the tunnel or on the surrounding roadway network;
- an interface module to acquire data from sensors and GPS devices installed on-board of the *vehicles transporting dangerous goods*;
- a module dedicated to simulate different traffic management strategies (response plans) and emergency scenarios, which is connected with the traffic simulation tools at macro-scale (MIAURB from D’APPOLONIA) and at micro-scale (AIMSUN), in order to model and evaluate the associated evolution of the traffic flows;
- three user interface modules for editing respectively road network and network characteristics, information about incidents and the response plans;
- a module, including three procedures, to estimate the *duration of the incident*, the *extent of the incident impact area* and the *delays* suffered by drivers in case of non-intervention;
- a module to *select the most appropriate traffic response plan*, on the basis of a predefined set of rules, and to help step-by-step the TCC operator through the tasks needed to *implement the plan*, including the provision of incident-related information to drivers and the application of traffic control measures on the road network affected by the incident; the set of rules used in the module is formulated by traffic experts who possess specific knowledge and expertise to solve traffic congestion problems; in the rule-formalising process, traffic simulation tools can provides data for deriving consistent rules for the selection of the best traffic plan in response to an incident;
- a path generation module to enable the shortest, fastest *routing of emergency response vehicles* from the various key locations, including hospitals, fire and police stations, to the incident scene;
- a module for *tracking* the vehicles transporting *dangerous goods*, on the basis of data received from sensors and GPS devices;
- an interface module to make available on the WEB the information about emergency situations and the traffic response plan under implementation.

### 4.3 TRIM prediction tools

The above mentioned software module dedicated to estimate the *duration of the incident*, the *extent of the impact area* and the *delays* suffered by drivers in case of non-intervention, incorporates three procedures:

- a first procedure implementing a statistical model using variables related to operational and incident-type factors, that can be realistically obtained in real time under incident conditions, and statistical parameters tailored and calibrated on the basis of the time experienced in past incidents occurred in the local area;
• a second and a third procedures, implementing two different algorithms based respectively on the deterministic queuing and on the shock-wave models, to calculate the queue length upstream the incident (for a period of 24 hours after the incident), the maximum queue length, the queue discharging time, the total cumulative delay and the average delay per vehicle.

A second method to estimate the incident duration, using a decision tree where the first decision is based on the incident type, will be also introduced in the above mentioned first procedure.

The maximum queue length, the queue discharging time and the delays are forecast by the second and third procedures, starting from the incident duration estimated by the first procedure, the estimated (by the TCC operators) reduction in the roadway maximum capacity and a careful prediction of traffic demand for the 24 hours after the incident.

The prediction of traffic demand is produced on-line by the adopted algorithm by means of a weighted linear combination between the long term predicted values, based on traffic historical data, and the actual measured values received from traffic field sensors.

The long term prediction of traffic demand, based on traffic historical data, are elaborated off-line and can be memorized as “typical profiles”, which are vector values reporting traffic flows and speeds for each time interval of 20 minutes (72 values a day).

The typical profiles are then corrected on-line with the actual values coming from field sensors. The weighting parameters in the linear combination are calibrated using, when available, local historical traffic data.

The different value produced by the prediction tools are then used for the selection of the most suitable response plan, together with the traffic flows and speeds measured by the field sensors located on the concerned roadway and on the possible alternative ways.

The plan selection tool enters into function when the estimated delay and maximum queue length are beyond predefined threshold values and is based on:

a. the incident severity (classified according typical situations),
b. the estimated incident overall duration,
c. the current/predicted traffic demand approaching the incident site,
d. the current/predicted traffic demand on the alternative routes.

The response plans, stored by the TCC supervisors in the TRIM system, are evaluated off-line, with the help of the traffic simulators, and classified on the basis of the resulting total travel time and total delays of vehicles.

5. CONCLUSIONS

Roadway and tunnel agencies are now more frequently asked to develop and improve incident management to expedite response and clearance processes and to minimize the traffic flow disruption and the potential for secondary incidents.
Traffic management is a key step of the complex incident management process as it can greatly reduce the amount and duration of the resulting congestion. Traffic management embraces the selection of the most appropriate traffic control strategies, such as signal modification and traffic diversion, and the dissemination of incident-related information to drivers to avoid the incident and adjust driving behaviour.

The paper has presented a DSS (TRIM) designed to assist traffic control centre personnel in determining the appropriate strategies, aimed to effectively and safely manage traffic in post-incident scenario, and in the execution of steps required for their implementation and control. TRIM has the capability to use both historical and real time sensor data, to collect and categorize incident information, to simulate all candidate traffic response plans prior to their implementation, to perform the immediate preliminary estimate of incident impacts in terms of duration, delay and geographic extent, to select and implement the most appropriate response plan and, finally, to model and control real time traffic conditions during incidents.

The proposed DSS will be soon tested under real conditions in the interurban high congested corridor extending from the southern neighbourhoods of Naples to the town of Sorrento. The corridor is defined by the “SS 145” roadway (named Sorrentina) suffering from relatively high incident rates and including a 1400 meters long tunnel.

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